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Application of Deep Grooved Polyester Fiber in Composite High Absorbent Paper

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ABSTRACT

High absorbent products such as diaper, incontinence and other health care products, derive their superior absorbency, in part, from the unique capillarity of their structure. Deep grooved polyester fiber, used in combination with chemical cellulose, enables the paper designer to engineer high capillarity into the paper product. A primary objective of this study was to enhance the rate of liquid phase transport within the paper structure in a component known in the trade as the "surge layer" or "wicking layer". This study has shown significant advantages in liquid phase flow rates in structures designed as polyester/cellulose composites. A secondary element of the study utilized an ultrasound instrument to quantify the liquid wetting rates.

INTRODUCTION

This research deals with a category of paper known as composite paper. Schwartz [1] has defined a composite material , i.e. composite paper, as a material system composed of a mixture or combination of two or more macroconstituents differing in form and/or material composition and that are essentially insoluble in each other. In this case the two macroconstituents are polyester fiber and cellulose fiber. The subject structure of this paper is a fiber based composite in which the cellulose fiber is the major component and the polyester fiber is not chemically bonded to the cellulose.

The demand for absorbent products in recent years has led to a significant amount of research in developing super absorbent materials. Many of these contemporary absorbent materials are both hydrophilic and insoluble in aqueous fluid [2,3]. A typical absorbent element contains an absorbent core composed of cellulose fiber filled with natural or synthetic polymer beads of high molecular weight. These polymers of starch-acrylonitrile, carboxymethyl cellulose or polyacrylate, although possessing high absorbency, create bulk and are therefore more useful in the absorbent core than in a wicking or surge layer which demands both continuous and high rates of liquid phase transport away from the source and to the absorbent core. The open literature identifies at least four areas of concern over the use of polymer granules or beads:

- gel blocking leads to immobility of the fluids within the product
- migration of the polymers within the product makes the fluid flow uncontrollable
- adhesives may be needed to bind the granules to the product and these may interfere with the fluid flow
- densely packed wood pulp and the absorbent polymer reduce the structure pore diameters which negatively influences the rate of fluid flow to the absorbent core

To address these concerns, several researchers in the field have emphasized structural considerations by advocating layering of two or more components [4,5]. This strategy aims at channeling the flow of the liquid through the conduits formed by the web.

Theory of Fluid Flow in Porous Structures

Regardless of the strategy employed, and in terms of the physical parameters of the structure, its porosity is largely responsible for the flow pattern of the liquid [6]. Formulas have also been developed to correlate flow rates with liquid properties such as viscosity, density, surface tension and contact angle [7]. The much used Lucas-Washburn equation has direct applicability to our present case. A commonly used form of this expression is the following:

$$dl/dt = (\gamma/\eta)\ (r/l)\ \cos\theta$$

The terms in this equation are:
l = length of the pore (may also be thought of as the depth of penetration)
t = time
γ = surface tension of the wetting liquid
η = liquid viscosity
r = radius of an ideal capillary in the structure
θ = the contact angle between the wetting liquid and the wall of the capillary

This model assumes that the capillaries in the paper structure are right cylinders. Therefore the rate of penetration of the structure is dependent upon pore diameter. In the case of this work the 4DG™ served to effectively increase the pore diameter in addition to providing a higher surface area than an idealized round cross section fiber.

Another related expression is one presented by Parker et. al. (10).

$$Vp = Kpt^{1/2}$$

The terms in this equation refer to the following:

Vp = volume of liquid absorbed (in a sized paper)
Kp = a rate constant
t = time

This expression suggests that under the circumstances of their study that liquid absorption rate decreased with the square root of time. As will be demonstrated in our work, the behavior of the experimental structures developed here also showed this declining rate of penetration with time.

Instrumental methods have also been developed to measure flow rates of fluids in absorbent structures. A recent example is x-ray computed tomography [8]. In the present study we employed the conventional gravimetric edge wicking procedure and a new instrument known as PDA™.

EXPERIMENTAL

Our approach to enhancing the porosity, and hence liquid phase flow rate, of an absorbent structure was to formulate a composite paper utilizing Eastman Chemical Co. 4DG™ (deep grooved) polyester fiber as the noncellulosic component. A unique feature of the 4DG™ fiber are the deep grooves or channels which occur along the longitudinal axis of the fiber [9]. The actual surface area of 4DG™ fibers is 2.3 to 2.8 times that of the same denier, round cross section, polyester fiber [9]. This is readily apparent in Figure 1. The material has been thoroughly described in the reference by Haile [9].

Our strategy was to employ the polyester fiber in a composite structure designed to simulate a wicking layer of a multicomponent absorbent product. A wicking layer is characteristically a hydrophillic layer with a high capillarity. It is the capillarity of this element which transports the liquid to the absorbent core.

Since the rate of liquid phase transfer from the source to the absorbent core is central to the overall performance of the wicking layer, it would seem most desirable if the wicking layer could enhance fluid flow simultaneously in both its Z plane and the X-Y plane. It was a further intent of this work to improve the performance of the wicking layer through design considerations which incorporate the above concepts.

The hypothesis of this work was that the liquid phase absorbency rate, and the overall quantity of fluid absorbed by an absorbent structure of a given weight, may be enhanced through the addition of designed fibers which possess unique surface functional features which will alter the capillarity of the structure. The objectives of the study were the following: 1.) To design a composite paper with an absorption rate greater than that found in a commercially available diaper wicking layer, 2.) To determine the influence of incorporating 4DG™ into a composite structure and its influence on both the rate of absorption and the absorption capacity, 3.) To compare the effect of weight percentage of 4DG™ on absorbency, 4.) To determine the applicability of the Penetration Dynamic Analyzer ™ to measure absorbency, and 5.) To compare the X-Y plane absorbency with the Z plane absorbency in the composite structures.

A series of Standard TAPPI Handsheets (T205-om-88) were produced to the following target specifications:

Basis Weight	21 g/m^2
Caliper	106 μm
Apparent Density	~ 0.2 g/cm^3

Handsheets were prepared to the above specifications using the following furnishes of 4DG™ based upon cellulose:

Handsheet Set	3 Denier 4DG™	6 Denier 4DG™
1	5%	
2		5%
3	10%	
4		10%
5	15%	
6		15%
7	20%	
8		20%
9	30%	
10		30%
11	40%	
12		40%

For comparison purposes, a 3 denier fiber diameter is ~ 17 μm and a 4 denier fiber is ~ 25 μm in diameter. For all penetration testing we utilized a synthetic urea fluid which was formulated as 10% saline water.

Absorption Testing With the Penetration Dynamic Analyzer™ (PDA)

The Mutek PDA instrument is capable of measuring the rate of liquid absorption in a paper material. It has the added advantage of a computer software package that is capable of analyzing the rate results graphically. It furthermore has the advantage of measuring the absorption rates in both the X-Y plane and in the Z plane independently of one another. This is a basic distinction between the conventional edge wicking test where the specimen is wetted only in the one plane while the PDA tester simultaneously wets the specimen in both planes.

The basic operating principle of the instrument is the application of ultrasound waves to record the movement of the wetting font of the penetrant from the outer surface of the paper structure into its core. As the wetting front progresses in the structure, the solid/liquid interface changes are perceived as attenuation changes in the ultrasound signals. The temporal relationship of these changes are depicted graphically on the computer and are the basis of the wetting rate figures shown in this manuscript. The principle of operation of the PDA instrument is the alteration of the transmitted ultrasound signal. The scattering, absorption and reflection from the ultrasound waves during the movement through the paper sample are responsible for the alteration of the ultrasound signal. The scattered, absorbed and reflected part of the ultrasound is changing during the wetting from the sample surface and during the penetration from the liquid into the paper. This alteration is recorded on a receiver and is shown graphically as the ultrasound intensity changes over time.

According to Mutek, the shape of the wetting curve is influenced by several factors. Initially when the liquid penetrant contacts the paper surface, an air film is on the surface which reflects the transmitted ultrasound. As the surface is rapidly wetted, the reflected air film is disappated and the signal rapidly increases. Following surface wetting, the penetrant enters the paper structure and the ultrasound absorption of the material continues to change. A wetted material absorbs less ultrasound than a dried material. The X/Y graphic of this event should show a positive slope during the penetration process of the liquid into the specimen. If the material is very compact, e.g. a copy paper, during the penetraion of the liquid the signal curve will show a negative slope dur to air bubbles enclosed in the wetted paper. These bubbles strongly scatter the ultrasound and the received power is decreasing. After the material is wetted, it is possible to measure the swelling of the fibers since the air in the fibers is replaced by the liquid. Hence, the air bubbles in the fiber are no longer able to scatter the ultrasound and the signal to the receiver is increasing during the swelling process.

By closely examining the differences in wetting curve characteristics, one can evaluate the changes in wetting properties between various structures. Through the evaluation of the wetting curve profiles, we were able to draw conclusions regarding the various interacting parameters which influenced the wetting performance of our experimental composite structures.

To calibrate the PDA, we began with a sheet of extruded polyethylene film. Since there is no wetting of the film, the transmission curve moves almost instantaneously to 100% (Figure 2). The resulting curve then is a simple horizontal straight line with a small increasing segment in the first milliseconds due to the reflection air film on the surface being replaced by the penetrant. This clearly represents a minimum of sonic activity, or sonic change, through the process of air replacement with liquid. This is as expected for an impervious polymer film. Another calibration specimen was a heavily coated paper. This paper showed a negative slope of the transmission level with time (Figure 3). The interpretation is that as the wetting front slowly moves into the structure, the displacement of air with liquid diminishes the sonic transmission. The unevenness of the curve is due to the unevenness of the progress of the wetting front and the unevenness of the air displacement from the sheet along the front. This uneven progress of the wetting front scatters the sonic wave and diffuses it. Still another calibration specimen was plain copy paper (Figure 4). The penetration rate of this paper was much greater than the first two as evidenced by the stronger negative slope of the transmission curve. The greater smoothness of the curve may be attributable to the decreased ultrasound absorption of the material which is electronically depicted as a higher signal level on the receiver.

Further calibration was conducted with a sample of tissue (Figure 5). With this sample the rate of wetting is so high that the initial transmission level never achieves the 100% seen in the earlier specimens. After the initial few seconds the rate goes to zero or even slightly negative for ~ five seconds and then continues to wet the paper, but at a continuously diminishing rate as the paper becomes saturated. A handsheet of 100% fluff pulp (Figure 6) also gave a wetting rate curve similar to that of the commercial tissue. This is to be expected based upon our understanding of the of the similarity of the structures of the two papers.

Wicking Layer Absorbency

The wicking layer of commercial diaper is generally composed of highly absorbent "fluff" cotton or wood cellulose fiber. Our design intent was to improve the liquid phase wetting rate in the wicking layer to a level which was not currently found in commercial products. When a body fluid contacts the wicking layer it is most desirable that it spread as rapidly as possible throughout the layer and away from the source. In an ideal structure the liquid would move directly (Z direction) to the storage layer where the polymer granules retain the fluid until the product is disposed of. If the Z direction flow, however, is not at a rate at least equal to the source emission rate, undesirable pounding of fluid may occur. To design a structure which would minimize this effect, we attempted to formulate a wicking layer with superior absorbency in both the Z direction and the X-Y direction. To assist in the design evaluation, we supplemented the PDA data with conventional gravimetric edge wicking evaluations.

RESULTS AND DISCUSSION

The time plots of liquid absorption rate in both the gravimetric edge wicking results (Figure 7) and the PDA ultrasound results (Figure 8) demonstrate that the absorbent structures formulated with 5% 4DG™ provided a higher rate of liquid uptake and a higher total absorption than the control wicking element formulated with 100% commercial fluff pulp. These data show that the high surface area polyester fibers enhance the absorption rate and the absorption capacity as determined by the grams of synthetic urea absorbed per gram of wicking layer per second.

The wicking layers formulated with higher percentages of three denier 4DG™ fiber, i.e. 10%, 15%, 20%, 25% and 30%, all showed similar enhancements in the absorption rate and the final absorbency. The wetting rate profile for all six of these 4DG™ concentration series showed the same trend of rapid initial wetting followed by an extended period of wetting at a rate that becomes nearly linear with time (Figure 9). In a related evaluation, the six denier fiber was used in a similar concentration series and showed an absorbency pattern as seen for the three denier fiber, however, the total absorption for the three denier (smaller diameter) fiber was greater than that found for the six denier (larger diameter) fiber (Figure 10). The decrease in absorbency with the larger diameter fiber was most prominent at the longer time intervals.

The PDA testing principles have been discussed above. The PDA curve shapes provide an approximate idea of the overall absorbency of the structure. We have concluded, based upon the PDA curves and the edge wicking data, that in the first few seconds of wetting the liquid enters into the wicking layer rapidly and quickly fills a high percentage of the voids in the structure located near the wetting front. After this initial surge, the remaining voids within the structure fill with the liquid at a much slower rate. This behavior is as suggested by Parker et. al. (10) and is shown in Figure 11. However, our observations show that the rate of wetting after the initial surge in a structure with 5% 4DG™ , i.e. the secondary wetting rate, is still greater than that observed for a structure made of 100% fluff pulp.

In very thin high absorbent commercial products with layered structures, one layer has to transfer liquid to the next as rapidly as possible. Depending upon the end use of the product, lateral spreading of the liquid may also be desirable. In the example of the diaper wicking layer it is desirable to have a high rate of liquid travel both in plane and out of plane. Our edge wicking evaluations have shown high rates of liquid movement in the Z direction in the wicking layer of commercial diaper products but considerably lower in the X-Y direction. The experimental composite absorbent structures described here have demonstrated equally high rates of liquid movement in both planes.

CONCLUSIONS

In this study we have designed and developed laboratory scale composite structures to serve as wicking layers in high absorbent products. These structures have been demonstrated to exhibit absorption rates greater than the comparison structures found in commercial diaper wicking layers. The work has further shown that the weight percentage of 4DG™ incorporated in the wicking layer directly influences both the rate of absorption and the absorption capacity.

In this study a new and relative unproved instrument, the PDA, was used in an effort to determine wetting rate data. The conventional gravimetric wicking tests were conducted in part to assist in the interpretation of the phenomena in the PDA curves. The PDA results can not be directly compared with the edge wicking results since the wetting geometry of the two tests are considerably different. We have attempted to use our good judgment in applying the data from the PDA, supplemented by the edge wicking data, to analyze the performance of our composite structures.

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REFERENCES

1. Schwartz, M.M., Composite Material Handbook, McGraw-Hill, 1984.

2. Salmen, L, and Seferis, J.C., Composite System for Natural and Synthetic Polymers, Elsevier Science Publication 313, 1986.

3. Crouse, B., Dagan, S.G. and Warner, E., Properties of Thermoplastic Fiber/Cellulosic Stratified Composite Paper, Tappi J., 68(7):94 ,1985.

4. Ryan, W. T., Creation of Ultrathin Absorbent Articles Through Use of Nonwovens/Superabsorbent Film Composite Structures, INDA TEC 92 - Book of Paper, 145, 1992.

5. Richson, G., Contoured Melt Blown Webs for Absorbent Products, TAPPI Proceedings, Nonwovens Conference, 71, 1991.

6. Miller, B., Wicking of Liquids in Nonwoven Fiber Assembly, TAPPI Proceedings, Nonwovens Conference, 216, 1991.

7. Crew, A.L., The Role of Fluids in Absorbency, INDA TEC 87 - Book of Paper, 475, 1987.

8. Kim, K., Fluid Migration in Noncellulosic Absorbents by Computer X-Ray Tomography, Nonwovens - An Advanced Tutorials, 271, 1989.

9. Haile, W.A., Deep Grooved Polyester Fiber for Wet Lay Applications, Tappi J., 78(8): 139, 1995.

10. Parker, I.H. and Wen, Y., Effect of Pore Structure on the Absorption of Liquid by Paper, 50th Appita General Annual Conference: Proceedings, Paper No. 2C13,349, 1996.

LIST OF FIGURES

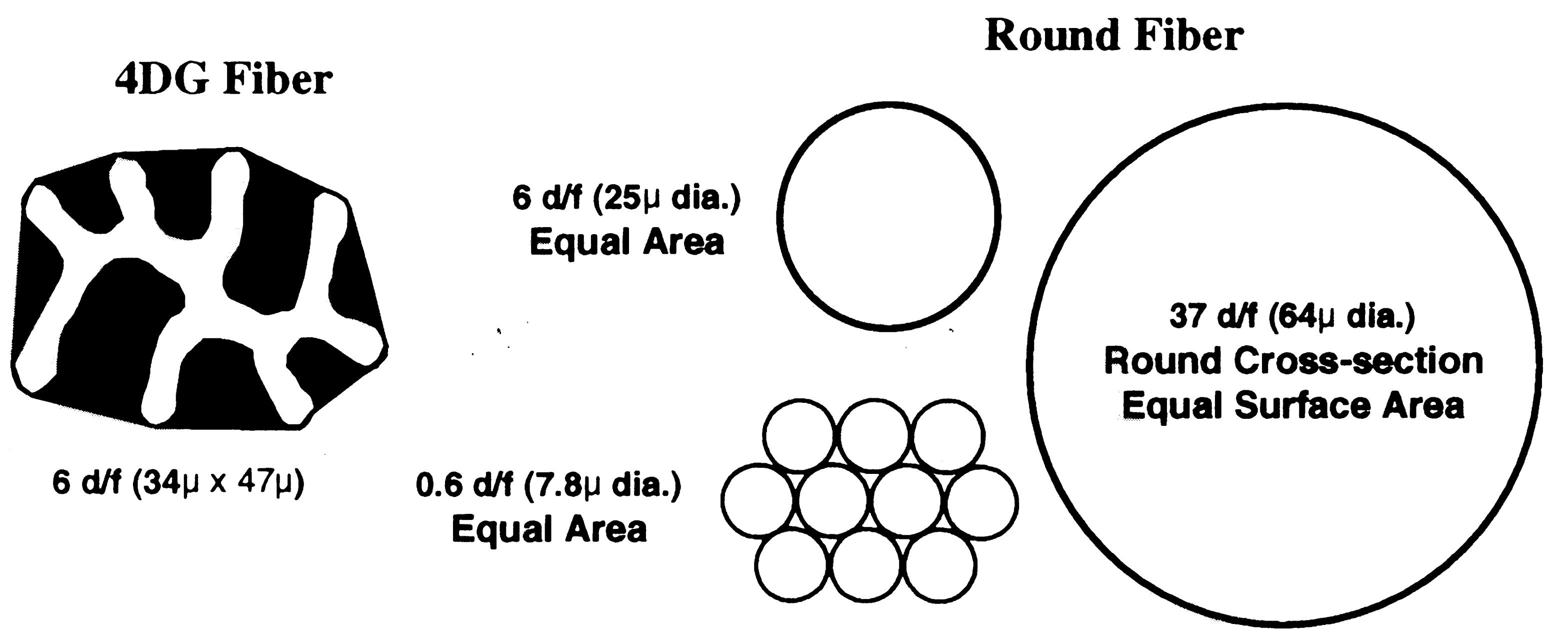

Figure 1. Cross section comparison of 4DG™ & round cross section fiber
Courtesy of the Eastman Chemical Company

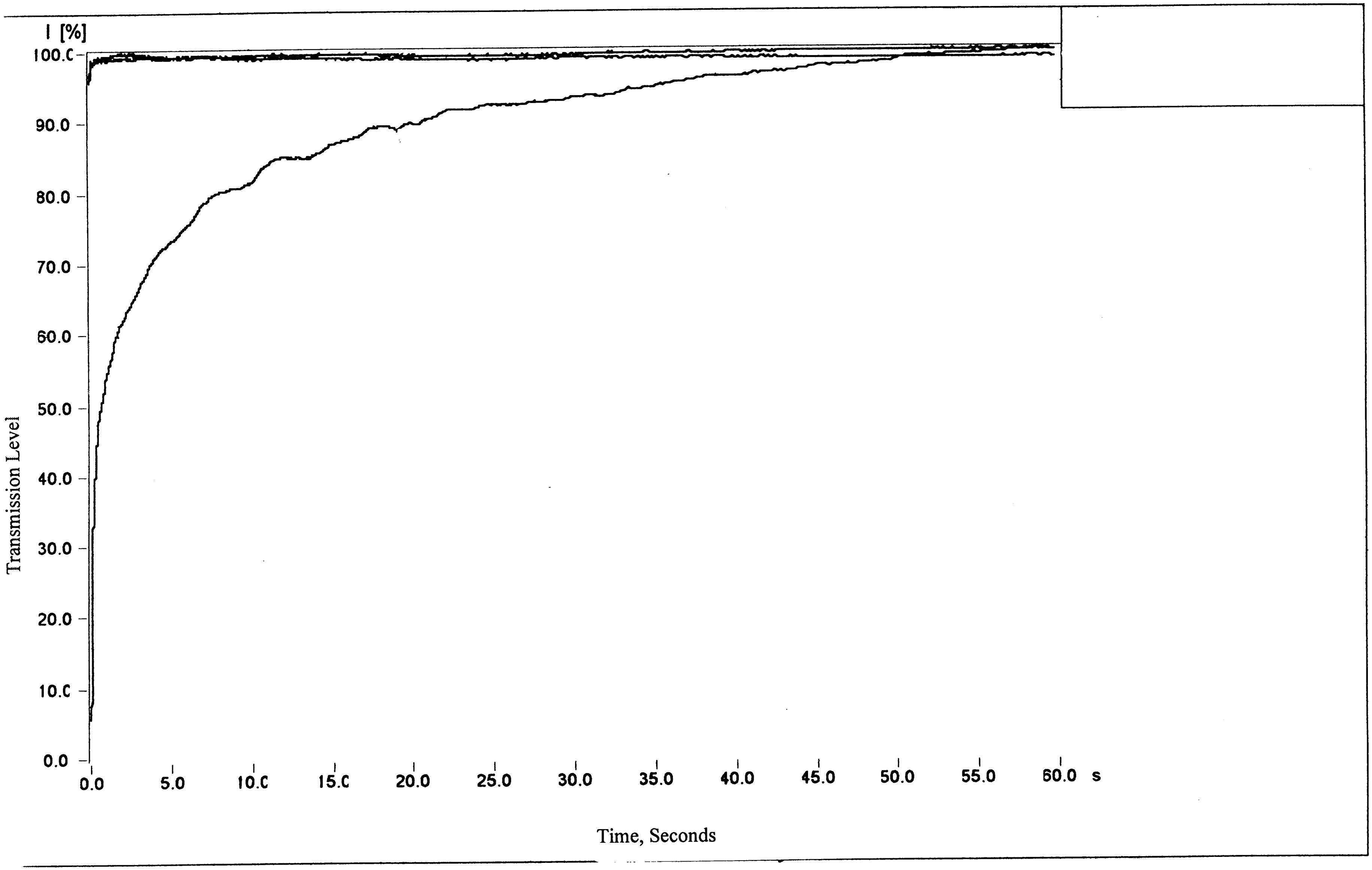

Figure 2. PDA wetting rate for polyethylene film & diaper wicking layer

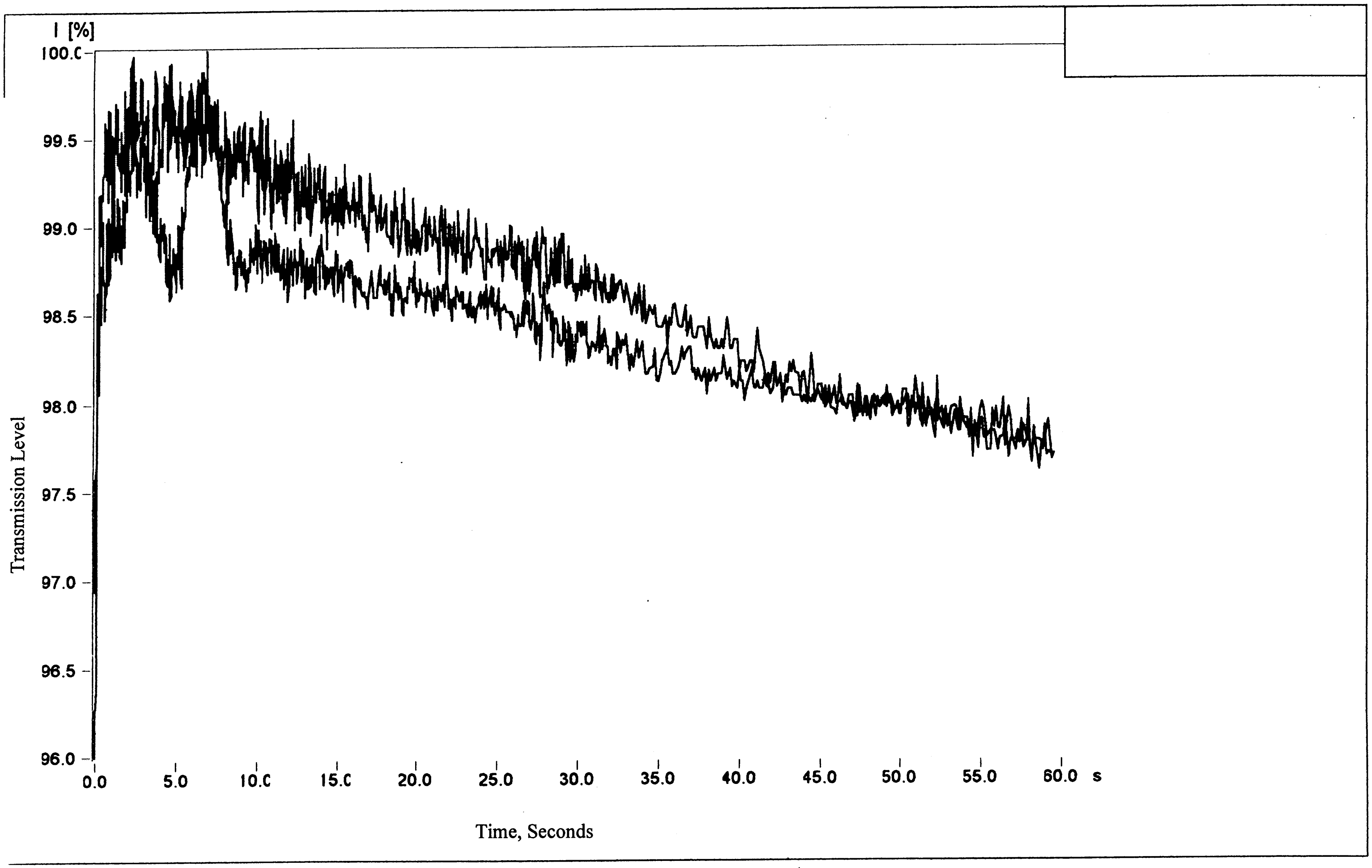

Figure 3. PDA wetting rate for coated paper

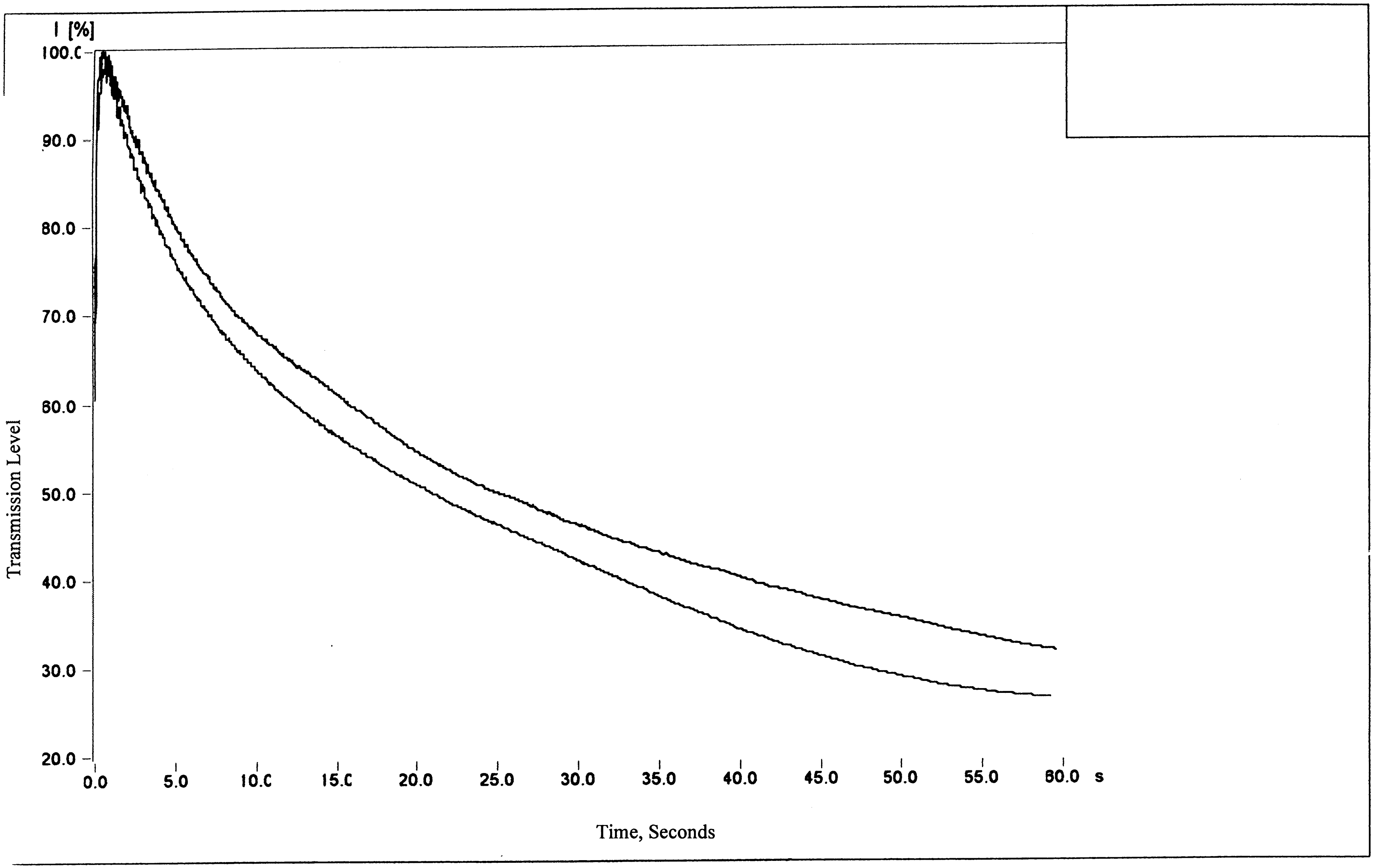

Figure 4. PDA wetting rate for plain copy paper

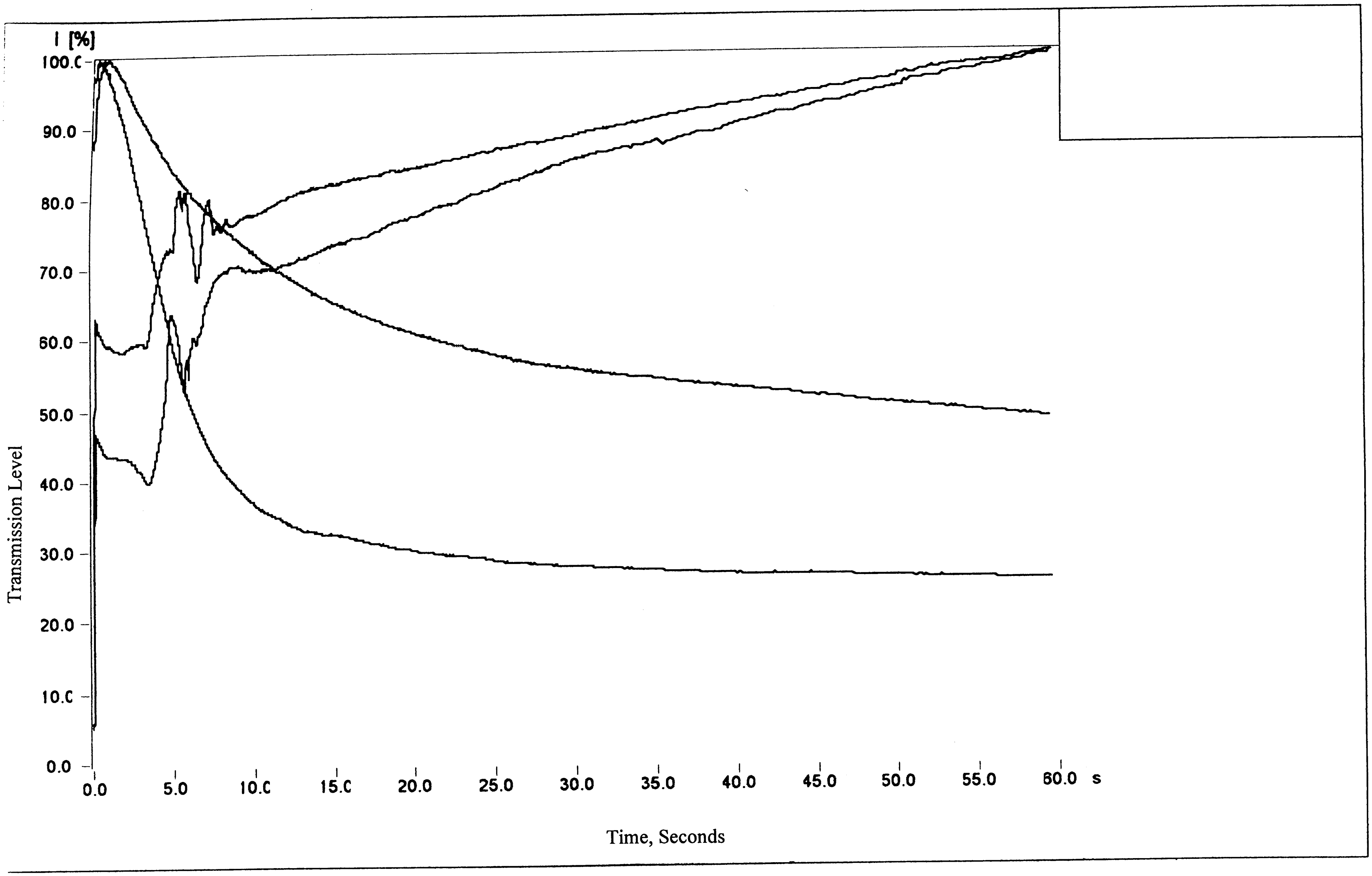

Figure 5. PDA wetting rate for tissue paper

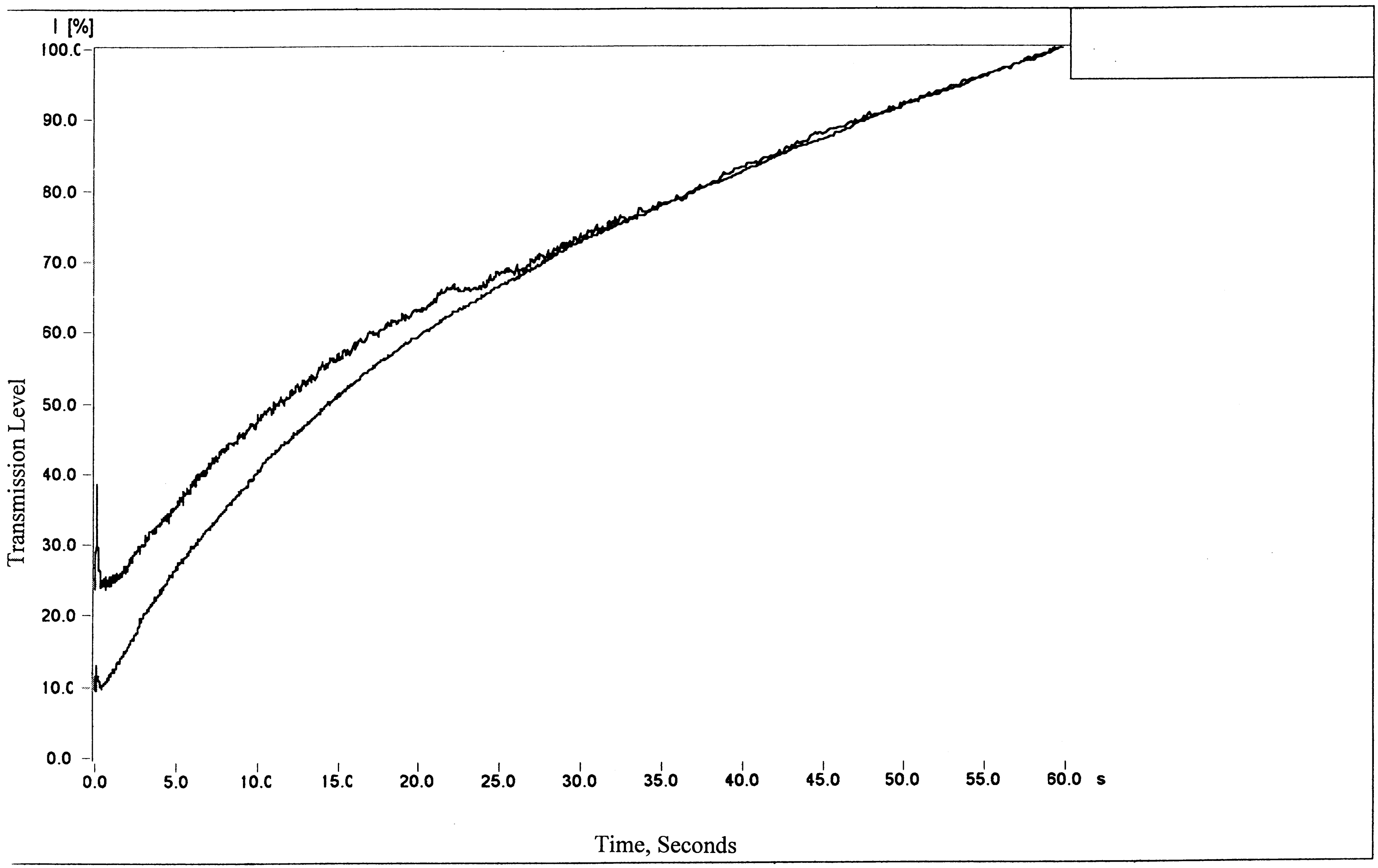

Figure 6. PDA wetting rate for 100% fluff pulp

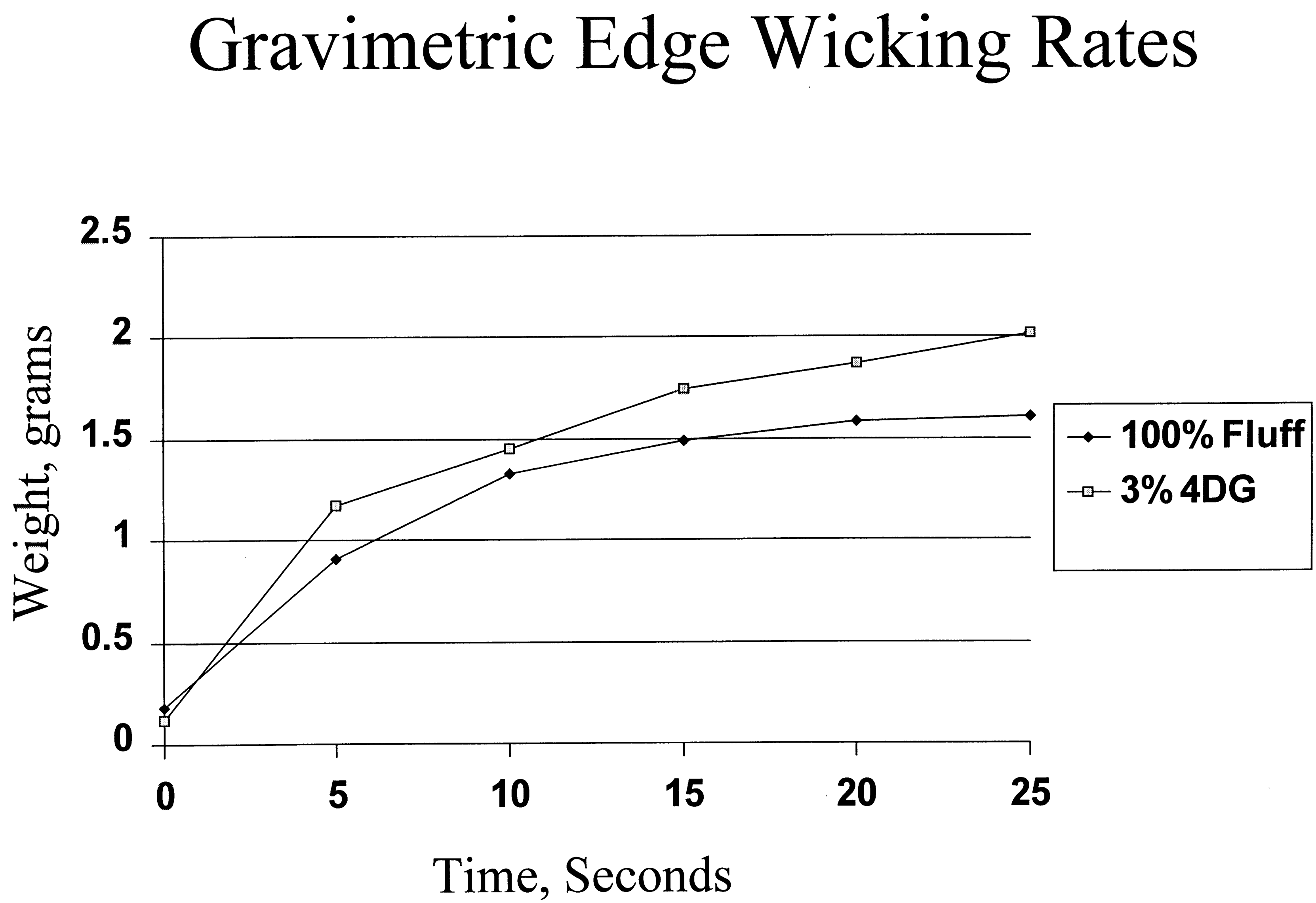

Figure 7. Gravimetric edge wicking rates, 100% fluff vs. 3% 4DG™

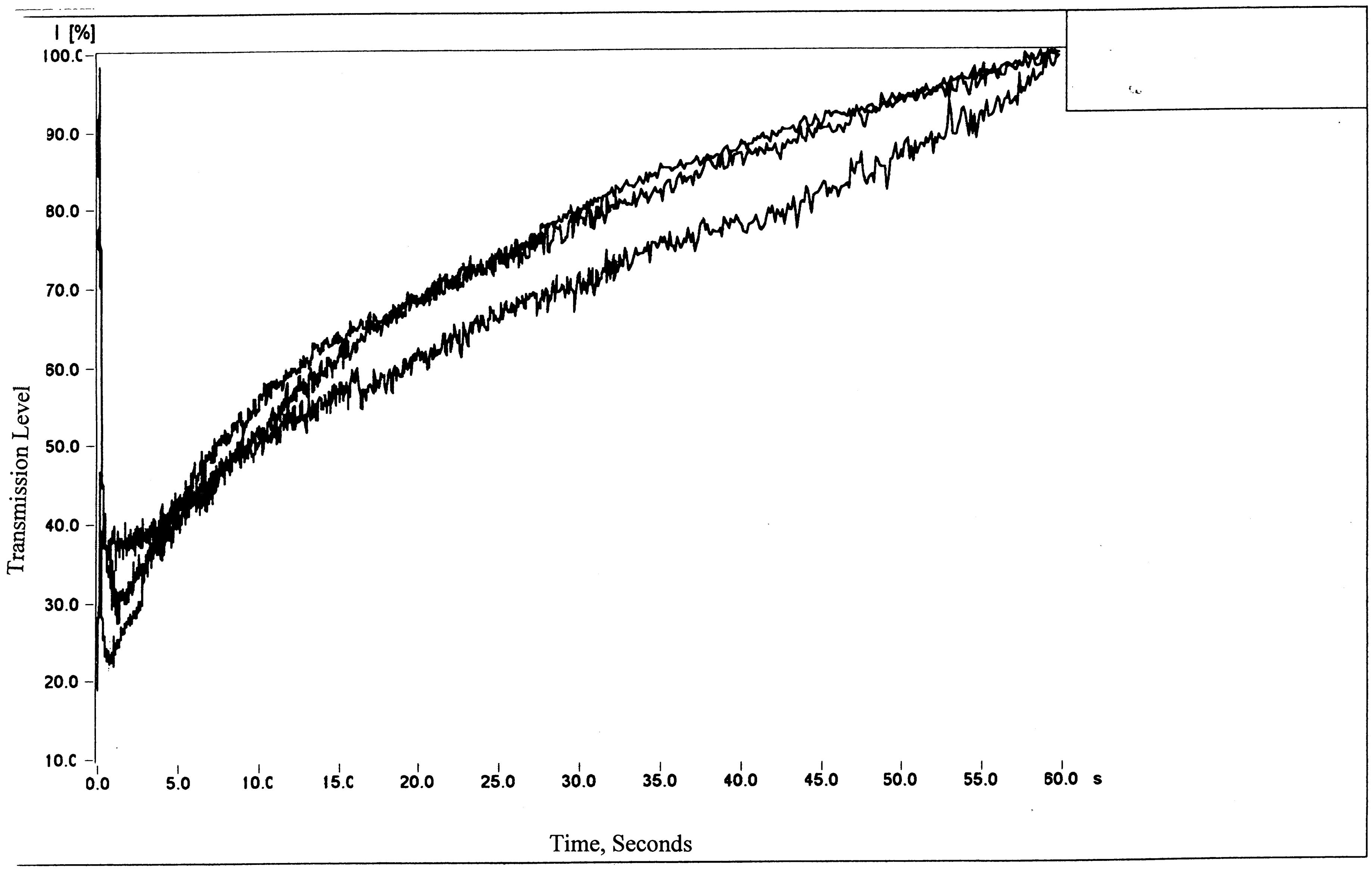

Figure 8. PDA wetting rate for 3% 4DG™ fiber

Absorbtion Rate as Influenced by %4DG Fiber

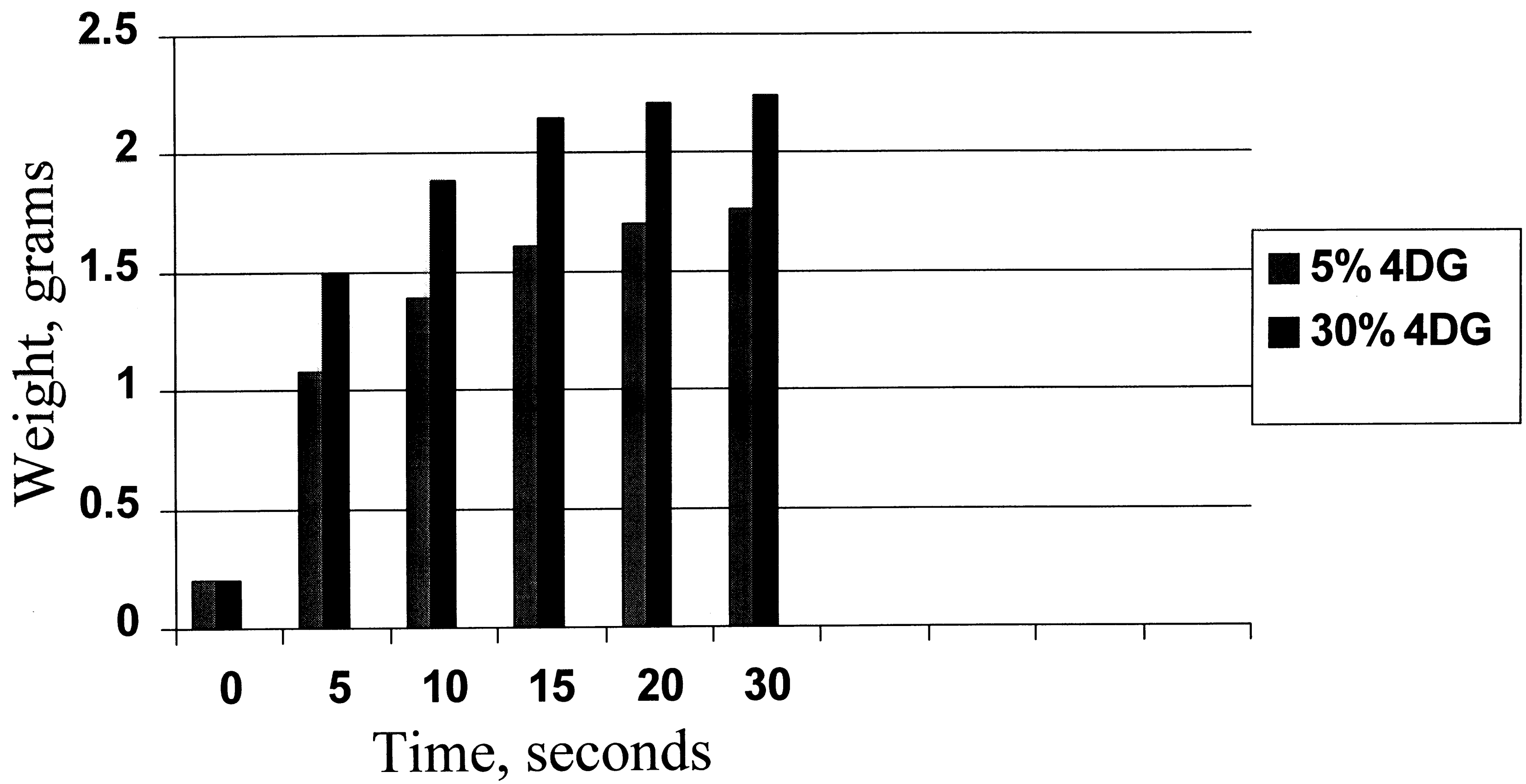

Figure 9. Absorption rate as influenced by %4DG™ fiber

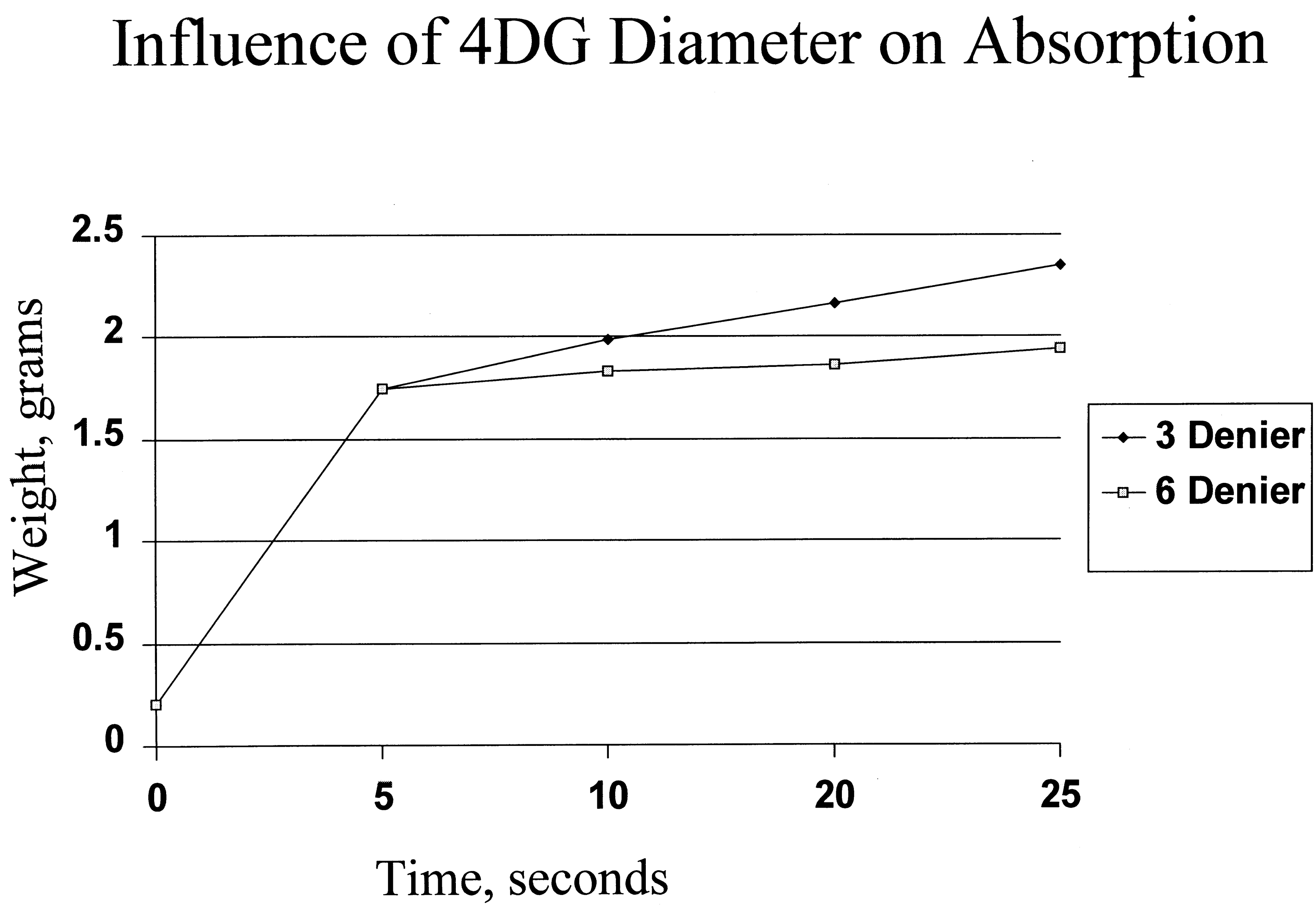

Figure 10. Influence of 4DG™ diameter on absorption

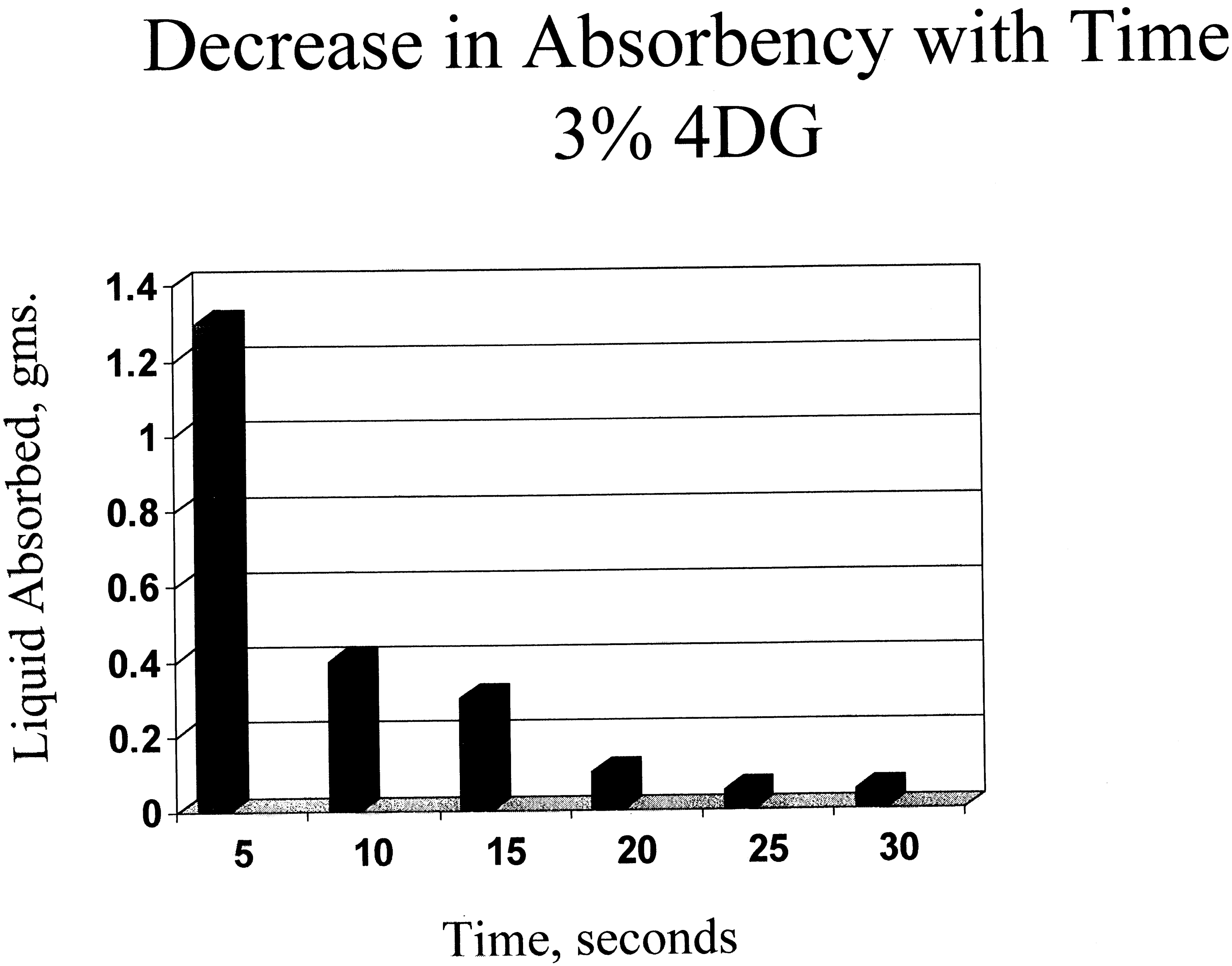

Figure 11. Decrease in absorbency with time